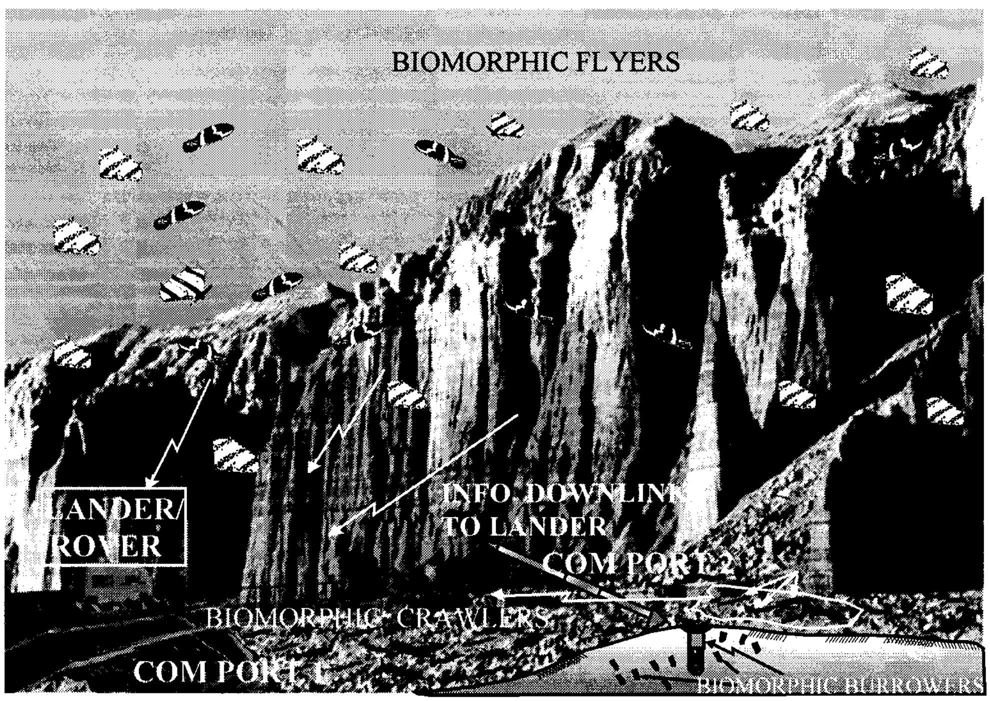
Final report- November 12, 1998

JPL D-16300

COOPERATIVE BEHAVIORS IN SMALL EXPLORATION SYSTEMS

Sarita Thakoor



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ABSTRACT

The objective of this study was to identify potentially useful cooperative behaviors for small space explorer systems that operate simultaneously. The report starts with a survey of emerging multirobot-multiagent techniques and their limitations. This is followed by a discussion about some of the uniquely powerful examples of cooperative behavior and self-organization observed in nature, specifically in the insect kingdom (e.g., in ant and honeybee colonies). Finally, the report presents several cooperative scenarios relevant to space exploration. These utilize a new class of small, dedicated, low cost, *biomorphic explorers* that capture some of the key features of biological systems. In particular, the cooperative mission scenarios utilize the potential rapid mobility and extended reach of biomorphic flight systems and provide detailed close-up imaging, in-situ geological and meteorological measurements, and sample return mission reconnaissance. The biomorphic flyers can also be utilized in a cooperative scenario for payload deployment and to deliver other biomorphic explorers.

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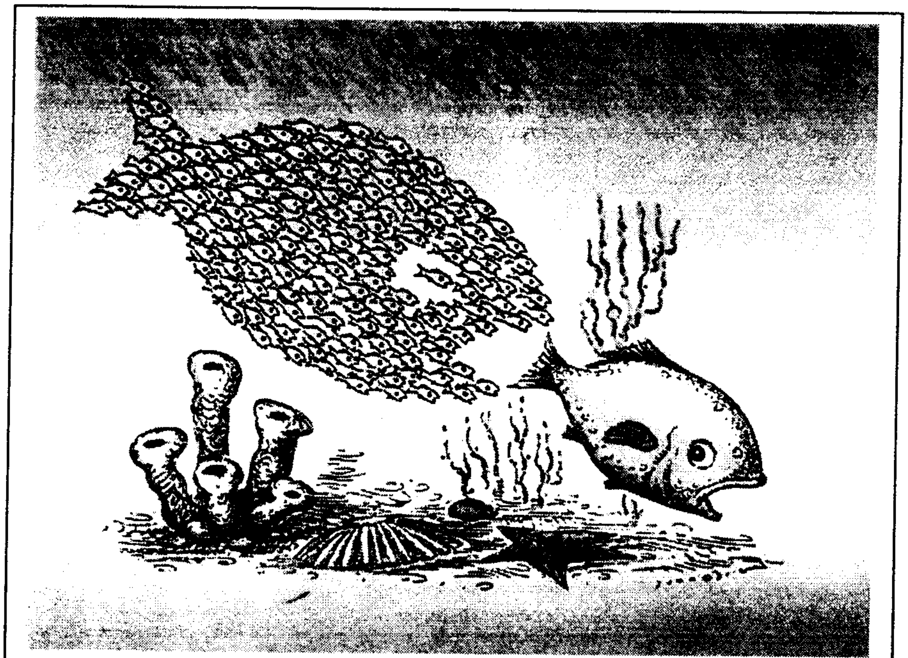

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Executive Summary

Solar system exploration, particularly of Mars and certain planet/satellites, could be substantially enhanced through use of a multitude of simple, small, somewhat autonomous explorers that as a group would be capable of "covering" large areas. A fleet of such explorers would have some form of limited communication with a mother ship (a larger lander/rover or an orbiter). In many cases, cooperation among all the "fleet-mates" could greatly enhance group effectiveness. The objective of this study was to identify potential useful cooperative behaviors for such explorers by surveying emerging multirobot-multiagent techniques and by assessing some of the uniquely powerful examples of cooperative behavior and self-organization observed in nature, specifically in the insect kingdom. For example, an adequately large number of ants is very good at locating areas of interest (such as food sites) and leaving trails to those sites to allow successful transport of food to the nest. Honeybees are even more impressive in their ability to communicate precise navigational information to other members of their families. Rather than a pheromone trail as used by ant, the bee uses a recruitment dance and the sun as a celestial reference to communicate the location of a food source. Such behavioral principles could be captured in planetary exploration functions such as scouting new territories for specific samples. Several cooperative scenarios relevant to space exploration are presented in this report. They utilize an emerging new class of small, dedicated, low cost, *biomorphic explorers* that would have some of the key features of biological explorers. These features include versatile mobility, adaptability to the environment, and cooperative behavior. Clearly, if the explorers would carry complementary sensor(s) and be equipped with different mobility modes (such as flight as well as surface/subsurface crawling/burrowing), the ensemble could enable a broad set of investigations. In particular, these coordinated cooperative mission scenarios would utilize the rapid mobility and extended reach of biomorphic flight systems and provide detailed close-up imaging, in situ geological and meteorological measurements, and enhanced sample return mission reconnaissance. The biomorphic flight systems could also be utilized in another cooperative scenario to deploy other specialized biomorphic explorers such as the crawler or burrower type. In fact, the cooperative scenarios developed in this study focus on using biomorphic flight systems for broad area in situ sampling of a planetary surface, mission reconnaissance, rover navigation support, and delivery of other specialized biomorphic explorers. Two key conclusions/recommendations of this study are (1) a broader and concerted study of cooperative behaviors in insect societies would be valuable, and (2) technologies needed to enable useful cooperative behavior in space exploration should be developed.

1. INTRODUCTION

The idea of "multiple cooperating robots" has been a subject of extensive study in recent years. In fact, it has generated a vast amount of multidisciplinary literature in research areas ranging from philosophy and psychology to mathematics and, of course, robotics. Specifically, the recent robotics literature[1-8] is full of basic (multi-agent theory, algorithms) as well as applied research (related to prototype hardware and application-specific software). It has been especially a fertile field for the artificial intelligence (AI), machine learning, and artificial vision researchers over the last several decades and has led to many conferences, workshops, books, and monographs on the subject (see the list below giving a sample of conferences/workshops in 1998). Although a lot of the past as well as ongoing work has looked at the cooperative behavior patterns exhibited by biological organisms, a large portion of the research has followed classical AI approaches to capture cooperation in human-engineered systems. The focus of this study, however, has been on those specific research approaches that are attempting to truly unravel complex, bio-behaviors, for the purpose of inspiring new ideas. Although higher in complexity, if successfully imitated, bio-inspired cooperative strategies / algorithms are expected to potentially lead to (1) a lot richer behavior for many applications, and (2) better functional / structural / configurational compatibility with the biomorphic explorers[48].

In any case, to achieve some meaningful goal through cooperation among many mobile entities requires effective sensing, communications, and processing/computing. The entities need to recognize their surroundings and their "teammates" to some extent. They need to have an effective way of communicating among the team members to be able to understand (and convey) intentions, capabilities, constraints, and opportunities. They need to be able to perform the necessary processing / computing to determine the next plan of coordinated action. They need to be able to communicate the results back.

This report is not meant to be a comprehensive review of the field. However, it discusses selected, ongoing, *bio-inspired,* cooperative robotics work (relevant to space exploration interests), reviews some of the recent work in actual cooperative behavior in biological systems (e.g., in ant and honeybee colonies), and finally presents a few cooperative scenarios relevant to space exploration. References are included near the end of this report.

A Sample of 1998 Conferences / Workshops

ICMAS'98
3rd International Conference on Multi-Agent Systems
Focusing on Theory and Practice of Multi-Agent Systems
Chair : Yves Demazeau Yves.Demazeau@imag.fr
http://www-leibniz.imag.fr/MAGMA/ICMAS98

ATAL'98
5th Int. W. on Agents Theories, Architectures, and Languages
Focusing on Theory and Practice of Intelligent Agents
Contact : Anand Rao anand@aaii.oz.au
http://www.elec.qmw.ac.uk/dai/atal

CIA'98
2nd Int. W. on Cooperative Information Agents
Focusing on Multi-Agent Systems (Information Discovery in the Internet)
Chair : Matthias Klusch Matthias.Klusch@informatik.tu-chemnitz.de
http://www.informatik.tu-chemnitz.de/~klusch/cia98.html

IATA'98
2nd Int. W. on Intelligent Agents for Telecommunications Applications
Focusing on Multi-Agent Systems & Telecommunications
Chair : Sayin Albayrak sahin@cs.tu-berlin.de
http://dai.cs.tu-berlin.de/workshops/iata98/iata98.html

CRW'98
1st Int. W. on Collective Robotics
Focusing on Multi-Agent Systems and Robotics
Chair : Alexis Drogoul Alexis.Drogoul@poleia.lip6.fr
http://www-poleia.lip6.fr/~drogoul/paris98/CRW98.html

ACW'98
1st. Int. W. on Agents in CommunityWare
Focusing on Multi-Agent Systems and Telematics
Chair : Walter Van de Velde wvdv@riv.be
http://www.riv.be/research/events/acw.html

MABS'98
1st. Int. W. on Multi-Agent Systems and Agent-Based Simulation
Focusing on MAS, Social Sciences & Artificial Life
Chair : Nigel Gilbert gng@soc.surrey.ac.uk
http://www.soc.surrey.ac.uk/research/simsoc/mabs98.html

RoboCup'98
International Competitions between Soccer-Playing Robots Teams"
Competition contact : Dominique Duhaut ddu@robot.uvsq.fr
http://www.bourges.univ-orleans.fr/Robocup98/index.html

2. COOPERATIVE BEHAVIOR IN ROBOTICS

A majority of the ongoing "cooperative systems" research tends to analyze the problem by systematically breaking it down into several areas such as task decomposition, sub-task allocation, achieving coherence amidst distribution of control, resolution of sub-goal conflicts, reasoning about activities of other agents, and inter-robot communication. In the development of cooperative robotics systems, a key challenge is to create systems that exhibit the desirable characteristics of fault tolerance, reliability, and adaptivity. A fault tolerant cooperative system should be able to detect and gracefully compensate for partial system failures, thus minimizing its vulnerability to individual robot outages. A reliable cooperative system should guarantee that its mission would be accomplished, within certain operating constraints, each time it is utilized. And, an adaptable robot team should be able to dynamically modify its actions as the environment or robot team changes over time. The following examples capture the essence of the current research directions.

Review of Ongoing Work:

a. The Center for Engineering Systems Advanced Research at the Oak Ridge National Laboratory (ORNL) is working on the theoretical aspects and algorithms for cooperating robotics. ORNL has developed an architecture, called ALLIANCE[9-10], that facilitates the fault tolerant cooperative control of heterogeneous mobile robots. One aspect of the current work is aimed at reducing the programming complexity of cooperative robotic teams through the automatic design of cooperative behaviors. Researchers have developed a cooperative robotics testbed to test their cooperative methodologies. This testbed consists of four Nomadic Technologies robots (illustrated in figure 1) equipped with a variety of sensors including odometric, tactile, sonar, infrared, 2D laser, vision, and compass sensors, as well as an indoor laser-based 2D global positioning system. In addition, the robots are equipped with a radio Ethernet system that allows inter-robot communication as well as communication to host development workstations.

Figure 1: Cooperative robotics testbed using Nomadic Technologies robots

b. Professor Fukuda, at Nagoya University, has developed a Cellular Robotic (CEBOT) [11-14, 52] system concept with an architecture that addresses self-organization principles. The CEBOT system consists of many robotic units (cells) with only simple functional capabilities. The CEBOT can reconfigure the whole system depending on given tasks and environments and can organize collective or swarm intelligence. The concept of the CEBOT is based on biological organization principles exhibited by organisms with numerous, loosely coupled natural cells. Several prototypes of the CEBOT have been developed and demonstrated under this project. This research project addresses several issues related to mutual communication among cells, the optimum dynamic knowledge allocation among cells, the reconfiguration strategy of the system, and artificial-life cooperative behavior modeling. This brings up many interesting research problems, including dynamic decentralized planning, dynamic distribution, and coordinated control (as well as associated implementation in hardware systems). Many applications are under consideration in space exploration; agricultural, medical, and construction applications; and in distributed inspection, monitoring, and surveillance systems.

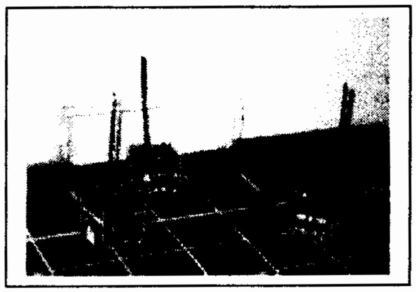

Figure 2: An example of a soccer playing robot team

c. The soccer playing robot teams (such as the example illustrated in figure 2) and the world-famous Robo-Cup competition certainly has attracted some great talent to the field of cooperating robotics. Building a robot to play soccer is a big challenge and requires a multi-disciplinary effort. The range of required technologies spans AI, robotic research, and embedded system design. This makes soccer-playing robots[15-20] the ideal demonstrators for a number of research activities and allows evaluation of various strategy theories, software algorithms, hardware architectures, and design techniques.

Figure 3: Another example: the GMD Robot

The Robo-Cup tournament is designed to handle real-world complexities, although in a limited world. Researchers from different fields can use the robot platform to work on problems such as real-time sensor fusion, reactive behavior, strategy acquisition, and learning, real-time planning, multiagent systems, context recognition, vision, strategic decision making and intelligent motor control. In fact, the recent soccer playing "mini" robots have started getting equipped with some sophisticated gear. For example, a robot (called the GMD robot) with a soccer ball, from the National Research Center for Information Technology Institute for System Design Technology, Schloss Birlinghoven, Germany, is illustrated in figure 3. It is equipped with:

- PC and Wavelan: The PC on each robot is a small laptop, and a wavelan Ethernet card is used for the wireless communication.
- Vision System: The vision system used to detect and track the ball consists of a camera and a circuit board from Newton Lab. (The soccer robot depends almost entirely on its visual input to perform tasks.)
- Sensors: Four color detectors determine the color of the surrounding objects. Each robot must distinguish the color of the ball, the goal, the wall, and other objects in the playground. By applying learning algorithms, fast object recognition is possible. Sixteen gray scale sensors are placed around the robot's body. They are able to measure the light intensity in the immediate neighborhood of the robot.
- Touch sensors: A bumper, constructed at GMD, detects a collision of the robot, e.g., with opponents or with the wall. A robot also uses infrared distance sensors.
- Motor: The motor speed is controlled using pulse width modulation. (A special brake function is included.)
- Micro-Controller: The robot is equipped with three 16-Bit micro-controllers that are connected via a CAN-bus.

3. LIMITATIONS OF CURRENT MULTI-AGENT SYSTEMS:

Distributed Artificial Intelligence (DAI) studies the use of cooperative systems of autonomous agents to solve difficult problems. Cooperative robotics can thus be seen as a subclass of problems in DAI. Methods of controlling the interactions between cooperating robots range from hierarchical[21] planning solutions, in which a central unit designates tasks for individual worker robots, to purely reactive societies[22,54] (e.g., "swarm" robots) in which there is no central agency and cooperation is inherent in the subsumptive rules that control the robots.

To date, control paradigms for cooperative robots either use explicit communication to pass state information between component robots or build rules for such interactions into reactive robots' control structure. Unfortunately, explicit communication, while a useful paradigm in designed systems, fails utterly when confronted with agents that are not an intended part of the system. For example, a robotic system designed with explicit inter-robot communication in mind will have a difficult time cooperating with a human being. Reactive approaches[23-27, 53], while robust and flexible in their limited domains, are too simple-minded for use in domains that require real reasoning. Reactive systems are difficult[28] to extend to complex domains, and frequently suffer from dysfunctional emergent behavior when their rule bases become complicated.

Observation, on the other hand, is a form of implicit communication in which the receiving agent acquires information about the acting agent in cooperating societies. With suitably cogent analysis on the part of the observer, observation retains both the power of communicating systems and the flexibility of reactive systems.

A system has been proposed[29,30] for observational cooperation in which agents infer group plans from their observations of external agents and reason about how best to cooperate. Issues include action and plan recognition, plan verification, synchronization, cooperation, and re-planning. The goal is to implement a complete observational system that includes solutions to each of these challenges.

4. ANT COLONY STUDIES

a. The behavior of ant colonies, specifically, how the ants coordinate complex activities like foraging and nest building, has fascinated researchers in ethology and animal behavior for a long time. Several behavioral models have been proposed to explain these capabilities. Algorithms inspired from the behavior of ant colonies have already entered into the mathematical field of multi-parameter optimization. This new approach to distributed optimization has been aptly named "Ant Colony Optimization (ACO)". ACO has been claimed to be successful in solving a variety of difficult combinatorial problems such as quadratic assignment, traveling salesman problems, routing in telecommunications networks, clustering and sorting problems, etc.

b. As an example of self-reorganization of mobile multi-agent systems, researchers at ETL/Japan are studying the foraging behavior of ant colonies. They have carried out numerical simulations of the behavior in order to observe what is really happening in the system. The simple behavioral algorithm of ants is often summarized as:

- At any given time, an ant is in one of these operational modes: search, attracted, trace, or transport.
- Search is the default mode. The ant moves randomly in a search mode.
- When an ant in any mode finds a bait-site, it switches to transport mode and carries a bit of bait back to the colony's nest.
- Bait can exist at several bait-sites. Ants in transport mode secrete recruitment pheromone along their transportation path, and this becomes the `trail.' An ant in transport mode returns to search mode when it reaches the nest.
- The trail evaporates and diffuses and produces a pheromone atmosphere.
- When an ant in search mode comes across a pheromone atmosphere, it switches to attracted mode, in which it is attracted by the pheromone and moves toward a position of higher pheromone density. If the pheromone disappears before the ant in attracted mode finds a trail, it returns to search mode.

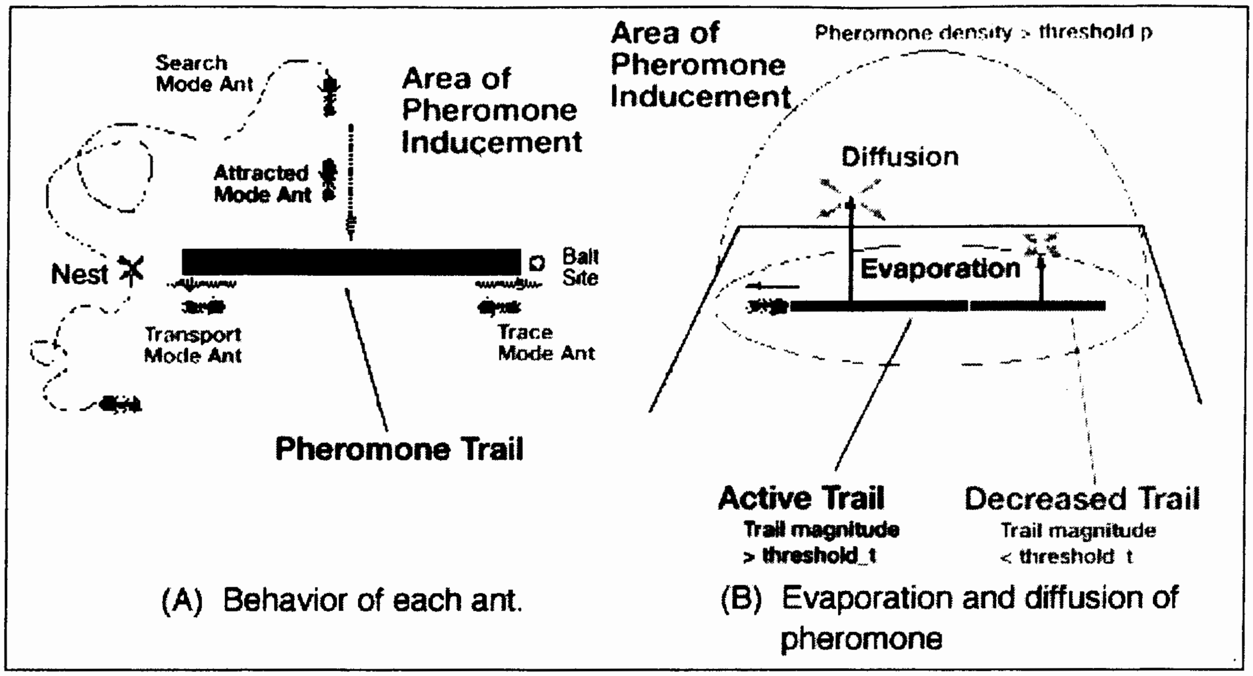

Figure 4: Schematic illustration of foraging behavior in ants

- When an ant in search or attracted mode finds a trail, it switches to trace mode, in which it traces the trail in the reverse direction of the nest. If the ant in trace mode cannot find bait at the end of trail, it returns to search mode.

This is an excellent representative decomposition of ant behavior and is available to copy in foraging, scouting, or exploring new territories. Furthermore, the simulations[31] at ETL/Japan clearly show the magic of numbers (in an ant population). For example, with a nest at the center of the environment and eight bait sites equidistant from the nest, 60 ants have trouble in effectively feeding themselves. Some of the search mode ants actually find a bait site during their random walk and generate a pheromone trail between the bait site and the nest. However, since the trail evaporates quicker than the other ants can get to the trail, continuous growth of the trail and continuous large-scale transport are not achieved. On the other hand, with 600 ants in the same situation, exponential growth of the trail occurs and a large-scale transport is achieved. The results show that enough ants need to exist in the system to conquer the time-delay problem associated with the gathering speed of ants and the evaporation speed of the pheromone.

c. Masao Kubo[32-34] from the Chaotic System Engineering Lab in the Complex Engineering, Department, Hokkaido University, Sapporo, JAPAN has been interested in multi-agent systems, especially, team plays. He has built artificial ant colonies in which each of the autonomous agents can learn by itself on-line. The agent can get wiser with experience and through communications. Through the study of simulated ant colonies, endowed with AI rules to deal with various situations, he has proposed a methodology for realizing distributed and autonomous system control. The major challenge in the control of multi-agent systems is the difficulty in generating actions by individuals that are globally suitable in a coordinated activity. The proposed methodology improves a colony's total activity through an individual learning process for each agent by using a Stochastic Learning Automaton (SLA) technique. In his case, the ant colonies play a game, similar to football, competing for food. This game environment serves sufficiently as a complex and changeable environment. The winning rate of the competition demonstrates the suitability of the coordinated motions.

d. A majority of the study of ant colonies behavior presented above enters the world of mathematics rather quickly, leaving the ill-defined but enormously rich world of biology behind. However, a few research efforts[35-36] are truly probing insect behavior that holds great secrets for engineers. An example is the, "Insect Behavioral Ecology and Life History Evolution" study by Naomi E. Pierce from the Museum of Comparative Zoology Labs, Harvard University. Projects in this laboratory are organized around several complementary themes, which include insect/plant interactions (see Figure 5), behavioral ecology, and life history evolution. In particular, they are studying aspects of the evolution of cooperation, using the symbiosis between ants and larvae of the Lycaenidae (Lepidoptera), as a model system. The larvae of about half the species in the Lycaenidae have myrmecophilous associations that range from parasitism to mutualism. Most species are herbivorous and feed on a wide array of plants, but some are strictly carnivorous, feeding on ants and homopterans. Because of their great interspecific diversity, the Lycaenidae provide an excellent opportunity to investigate the selective forces that shape the evolution of different strategies of life history in individual species.

Figure 5: Picture representing insect/plant interactions

Current work addresses two main areas of research. First, field and laboratory studies are being conducted to understand the behavioral mechanisms that promote and maintain species-specific ant associations. The aim is to determine why certain species of lycaenids have general interactions with many kinds of ants whereas others associate exclusively with only one species. Lycaenid caterpillars secrete chemicals that insure favorable recognition by ants, and researchers are characterizing the compounds used in this interspecific communication. The most intriguing communication method employed in the insect kingdom is where both larvae and the pupae of many species produce substrate-borne vibrations, or stridulations. This is currently a subject of research to understand the role of these acoustical signals in interspecific and intraspecific communication.

Next, the Harvard University team is also interested in the evolutionary consequences of specialization and the role of ant associations in the diversification of the Lycaenidae. Overlapping requirements of protective ant species and appropriate host plants may result in population restriction and subdivision of myrmecophilous Lycaenidae, and this has possibly led to faster rates of evolution. Within species, researchers are using molecular techniques to assess levels of polymorphism that may correlate with particular life history parameters measured in the field. Between species, they are using sequence data to estimate the extent of divergence between species in selected genera and to reconstruct the phylogenetic history of the family. This will provide the basis for a comparative study of life history characteristics of the Lycaenidae. At a first glance, this work may appear far from the subject of cooperative robotics. However, it is important to recognize that the diverse richness of team behavior observed in the insect kingdom clearly has its origin in the slight variations in the evolutionary paths followed by the different species.

The Harvard team is also pursuing the following:
(1) Analysis of the evolution of visual systems of butterflies, honeybees, and other invertebrates; (2) study of the development of wing patterns in butterflies, (3) investigation of the evolution of silks produced by spiders and insects; (4) identification of genetic differences that affect the susceptibility of plants to insect herbivores; and (5) analysis of geographic variation and costs / benefits of interspecific interactions in a number of model systems including ant/plant relationships, fungal/insect associations, and lycaenid/ant interactions. Results of this work will have direct relevance to design and development of large heterogeneous, but highly interactive and cooperative, explorer teams capable of multi-modal communications.

5. HONEYBEE BEHAVIORS

a. Mathematics of the Honeybee Dance

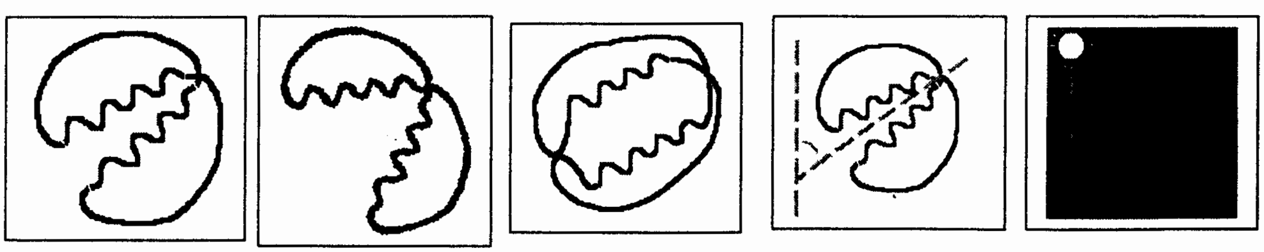

Figure 6: Illustrations of the Honeybee Dance

When a worker bee finds food, it travels back to the hive and relays, with uncanny precision, the direction and distance to the food source. In 1965 Karl von Frisch published[37] a paper explaining the mechanics of the dance based on his forty years of observation. What von Frisch found was that the returning honeybee conveys a lot of information to its fellow-bees during the "waggling" part of its dance (see Figure 6). If the food source is far away, the waggling lines are close together, and the whole dance resembles a kidney bean. As the distance to the source decreases, the angle between the waggles increases up to some critical value (that depends on the species of bee). At that point, the entire dance changes and the waggles become two parallel lines. The language of the geometry "spoken" by the bees is so precise that the angle between an imaginary vertical line on the hive and the bisecting line of the waggles is the angle between the projection of the sun on the horizon and the food source.

In 1997, Barbara Shipman[38] from the University of Rochester, an expert in mathematical analysis of a flag manifold (a six-dimensional space) and mapping groups from the manifold onto a 2-D surface, found that the groups greatly resembled the path of the honeybee dance on the honeycomb. This discovery has left biologists truly wondering. How could a creature with a brain consisting of only a million neurons carry out the six-dimensional calculations? What evolutionary mechanisms could have allowed this dance to develop in the first place? Shipman herself is questioning whether it is a pure coincidence.

b. **Bees as Environmental Monitors**

Researchers working at the Aberdeen Proving Ground in Maryland have found[39] that they can use bees to monitor a wide area for dangerous mustard gas residues from chemical weapons disposal sites. In addition, the free-roaming bees bring back samples of other hazardous materials to their hives, and an electronic network can alert army beekeepers to changing field conditions. The Proving Ground has areas onsite where chemical weapons residues were landfilled. Bees from monitored hives visit an area up to a half-mile in radius on the post. They bring back traces of metals, toxic organics, and even volatile chemicals along with the pollen stuck to their bodies. When computers detect erratic behaviors among the bees, such as queens walking outside the hive, built-in hive monitors collect air samples for laboratory testing. An important point is that statistically the bees very quickly learn to avoid areas that are unpleasant to them. The "scout" bees somehow communicate to others about their findings and "guide" them in the right directions. The monitoring method was developed by Garon C. Smith, Jerry Bromenshenk, and researchers at the University of Montana at Missoula. The landfill was a five acre mess called Old O-Field. The dump was used for dumping research and production wastes, unexploded weapons, white phosphorous, and munitions. In 1996 robotic and remote controlled bulldozers were used to install a permeable sand and gravel cover that would prevent access by trespassers, contain explosions, and prevent air contact with the spontaneously flammable phosphorous. The bees were on hand to warn the operators (working 2000 feet away) of chemical releases. Sensors and air monitors tracked bee activity levels and air quality inside the hive. These sensors reported to operators' computers. Heavy metals were determined by analyzing the collected bee pollen and the bodies of the bees themselves. Some of the compounds successfully detected included: PCE, carbon tetrachloride, TCE, diesel fuels and gasoline, benzene, p-dichlorobenzene, naphthalene, and acetophenone. Limonene and other components of the hive itself were ignored. Mustard gas itself was not detected, perhaps because much of it was converted into thiodiglycol, which then percolated into groundwater. Researchers believe that in the future, bees could be extremely useful in times of war.

c. **Celestial Compass in Honeybees**

Bees are inherently able to fly under the full blue sky to a distant food source with excellent navigation and communication capabilities. Further insight into this process was provided in the famous experiment[40] by Wehner and Rossel. The experiment consisted in having the bees perform their recruitment dances underneath a dome that restricted their skylight vision to a small patch of sky. The result was astounding. The bees made large navigational errors. A conclusion is that the bees were fooled into using an invalid celestial reference.

d. **Foraging Behavior of Bees**

When a bee finds a nectar source, she goes back to the hive and relinquishes her nectar to a hive bee. Then she can exhibit one of at least three behaviors. She can start to dance to indicate to other bees the direction and the distance to the food source; she can continue to forage at the food source without recruiting nest mates: or she can abandon her food source and become an uncommitted follower herself. It has been shown experimentally that a bee has a relatively high probability of dancing for a good food source and abandoning a poor food source. These simple behavioral rules allow the colony to select the better quality source. Camazine et al. [41,42] have confirmed with a simple mathematical model based on these observations that foragers can home in on the best food source through a positive feedback created by differential rates of dancing and abandonment based upon nectar source quality. If the colony is offered two identical food sources at the same distance from the nest, the bees exploit the two sources symmetrically

6. SELF-ORGANIZATION IN INSECTS

Self-organization was originally introduced in the context of physics and chemistry to describe how microscopic processes give rise to macroscopic structures in out-of-equilibrium systems[43,44]. Recent research that extends this concept to ethology suggests that it provides a concise description of a wide range of collective phenomena in animals, especially in social insects[44]. This description does not rely on individual complexity to account for complex spatiotemporal features, which emerge at the colony level, but rather assumes that interactions among simple individuals can produce highly structured collective behaviors.

Self-organization can be applied to the study of various aspects of social life in insects. A choice between two equivalent food sources by ants can be performed collectively by means of self-organization. Foragers are initially evenly distributed between the two sources, but one of the sources randomly becomes slightly favored. Then, this difference may be amplified by recruitment, since the more foragers there are at a given source, the more individuals are recruited to that source, especially if pheromone trails are involved[45]. Also, when a source is richer, foragers exploiting this source lay more trails than those exploiting the poorer source did, leading the colony to select the richer source[45]. Similarly, the interplay between recruitment and travel time or individual orientational memory[46], leads to the collective selection of the shortest path. In bees, as was discussed earlier, food source selection relies not on chemical trails but on recruitment through dances. It has been argued[42] that self-organization is also at work in the development of the characteristic pattern of brood, pollen, and honey on the combs of honeybee colonies.

7. BIOMORPHIC EXPLORERS:

Biomorphic explorers are small, dedicated, low cost explorers that capture some of the

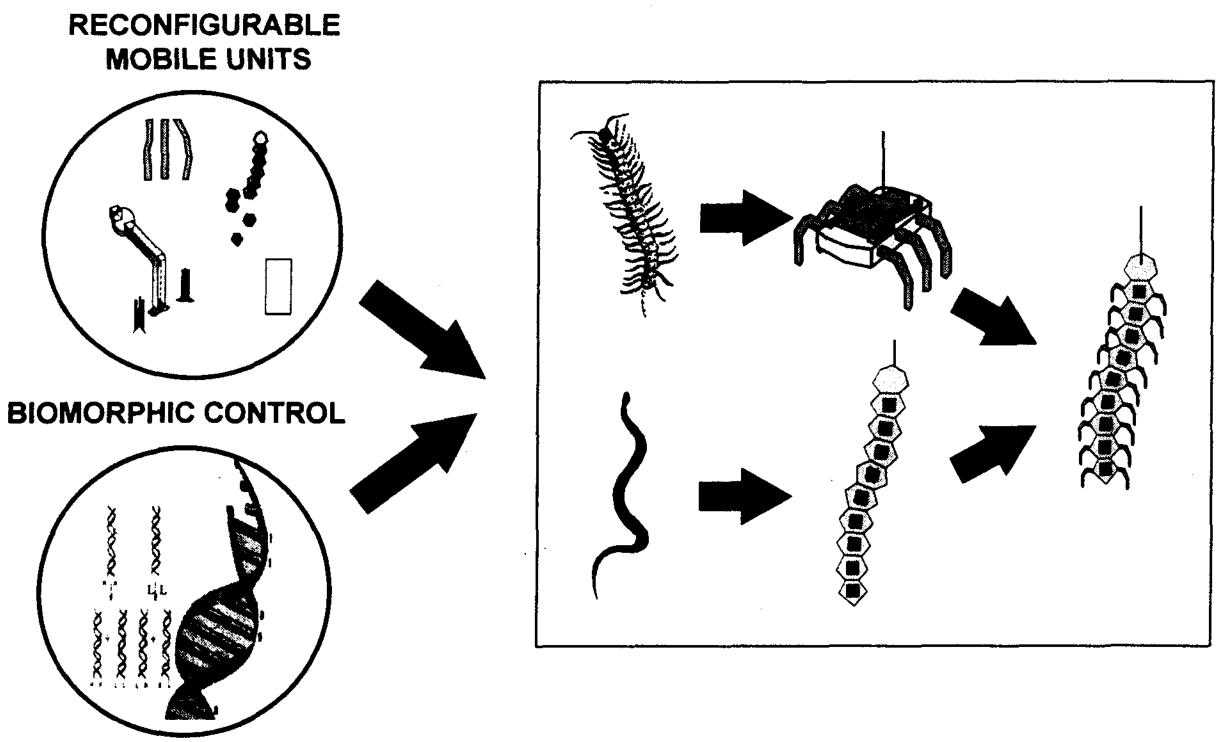

Figure 7: Schematic illustration of the concept of Biomorphic Explorers

key features of biological systems. The concept of bio-morphic explorers, as illustrated in figure 7, offers a unique combination of reconfigurable mobile units and their control by adaptive, fault tolerant, bio-inspired algorithms to autonomously match changing ambient/terrain conditions. Biomorphic explorers offer the potential to obtain significant scientific payoff at a low cost by utilizing the power of a large number of co-operatively functioning units. This is analogous to the approach seen in insect societies.

A recent NASA study[47] suggested that biomorphic explorers could be feasible and cost-effective. An important application would be to use them as scouts in future planetary exploration where they would look for samples/sites of interest. Inspired by the world of insects and animals, the well-proven natural 'explorers' on this planet, biomorphic explorers represent an exciting alternative to traditional labor-intensive telerobotic operations. The study concluded that combining flexible reconfigurable mobile units and biomorphic controls would offer, for the first time, a possibility of autonomous exploration with adaptation to varying terrain conditions. Figure 8 shows examples of reconfigurable mobile systems found in nature both in the surface mobilty and aerial mobility domains that are specifically suited and adaptive to their specific environment

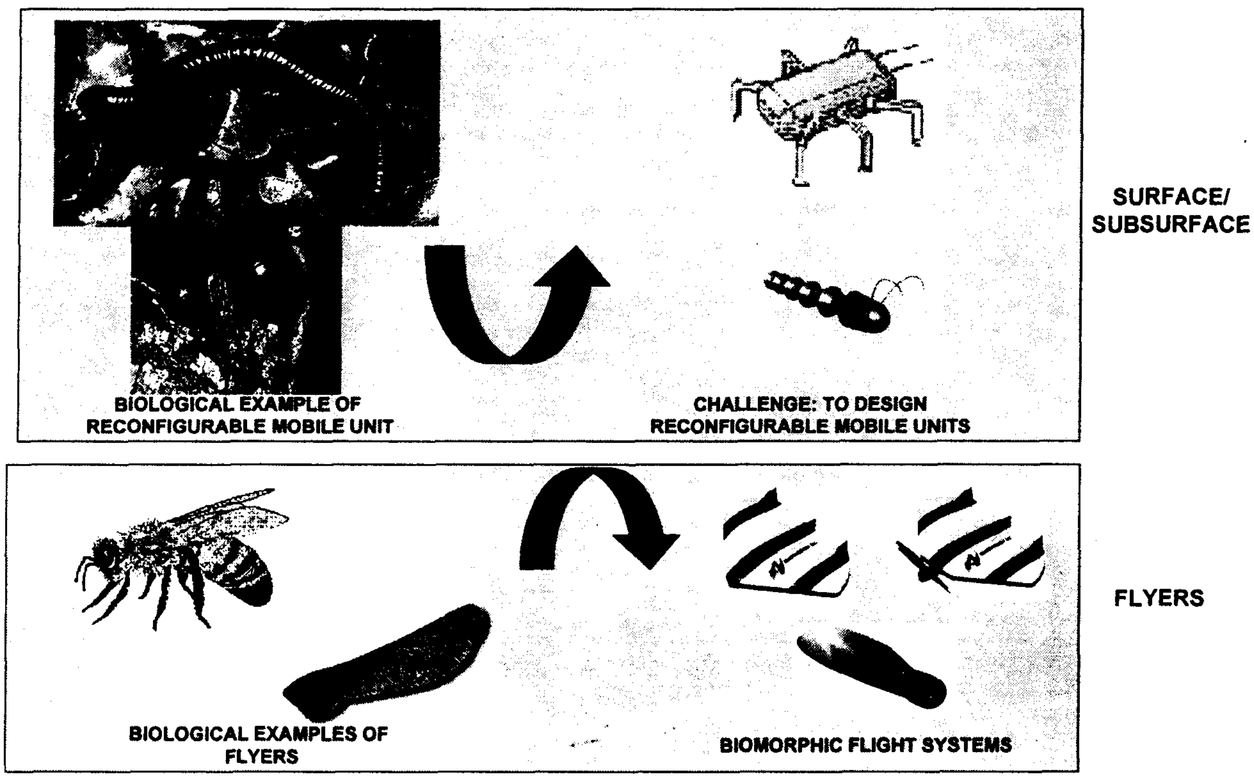

Figure 8: Reconfigurable mobile units : Inspiration from nature for biomorphic systems

and function . Biomorphic explorers[48] could provide enhanced spatial access and ease of production with low recurring cost, due to their simple design. This level of autonomous exploration would be beneficial to several planetary science goals. These goals include: scouting for conditions compatible with life to lead us to the right spots that may hold samples of extinct/extant life; in situ sensing to obtain physical, meteorological, and chemical data on unexplored planetary surfaces; and investigation of previously inaccessible locations. On Earth, biomorphic explorers would offer new capabilities for exploration, surveillance, advanced warning systems, and access to difficult environments.

In-situ, autonomous exploration and science return from planetary surfaces and subsurfaces would be substantially enhanced if a large number of small, inexpensive, and therefore dispensable, biomorphic explorers equipped with dedicated microsensors could be spread over the surface by a lander or a larger rover. Mimicking biology, such biomorphic explorers may possess animal-like mobility and adaptability. Their low-cost and small size would make them ideal for hazardous or difficult site exploration, inspection, and testing. Their dedicated sensing functions and maneuverability would be valuable in scouting missions and sample acquisition from hard to reach places. Such biomorphic explorers would complement the capabilities of the larger and relatively expensive exploration platforms/modes (e.g., orbiters, landers, rovers, and aerobots). Also, biomorphic explorers may possess varied mobility modes such as surface-roving, burrowing, hopping, hovering, or flying to accomplish surface, subsurface, and atmospheric exploration. Preprogrammed for a specific function and spread over the exploration site, they could serve as intelligent, downlink-only beacons that autonomously look for objects of interest. It was conceptualized[48] that, in a hierarchical organization, these biomorphic explorers would report their findings to a next higher level of exploration (say, a large conventional rover) in the vicinity. This would allow for example more wide-spread and affordable exploration at lower cost and risk by combining a fast rover to cover long distances and deployment along its route of numerous biomorphic explorers for in-situ sensing and local sample analysis/acquisition. Section 8 details on a few cooperative exploration scenarios enabled by the use of Biomorphic explorers.

7.1 Biomorphic Flight Systems:

The biomorphic flight systems are within this class of biomorphic explorers. Two thirds of all living species on earth are capable of flight. Nature provides the ultimate example of alternative configurations to solve the problems of flight. Every insect or bird is uniquely different and each is optimally adapted to its specific niche–to literally its mission in life. Similarly with man's aerial creations from gossamer light human-powered aircraft to the tons of metal of a supersonic jet or the complexity of a helicopter, each is also refined for its specific, intended purpose. Biomorphic flight systems could follow the same trend. A number of different modes of flight and configurations could be developed, each of which would be optimized for achieving a particular combination of design parameters in accordance with the varied, yet specific interests of the customer community to provide solutions to exploration needs.

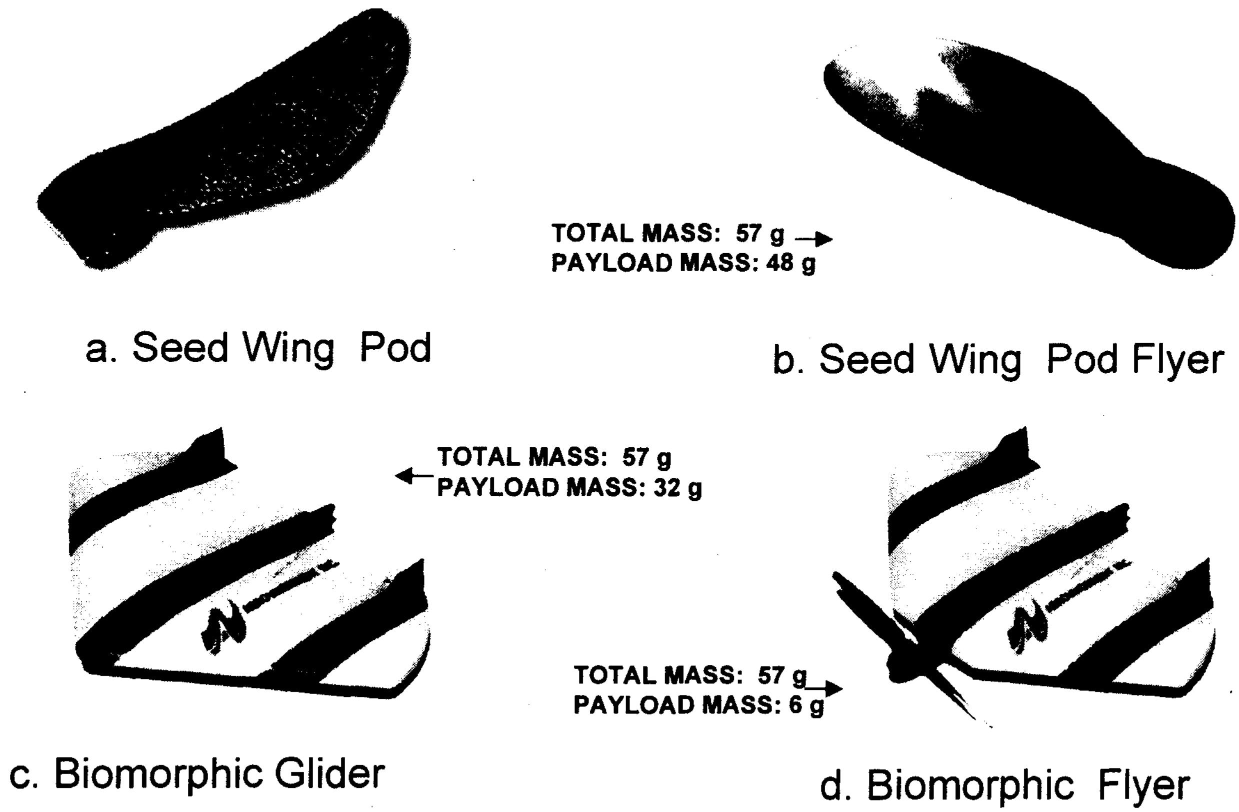

Figure 9: Biomorphic Flight Systems: Some Examples of Conceptual Ideas

A new idea which holds promise for a more robust and compact alternative to the parachute for small payloads is inspired by the biological world, particularly the seed wing pod from a plant (illustrated in figure 10a). It inspired a seed wing flyer design shown in figure 10b. The cooperative behaviors of bees and other creatures, in combination with the flight modės of birds and soaring birds, have lead to ideas for adaptive biomorphic gliders and biomorphic powered flyers (shown in figure 10c and 10d). Soaring birds (e.g., frigate bird, albatross, and hawks) use wind currents to stay aloft for hours or even days using little power to search for food or travel great distances. Biomorphic flyer concepts can be envisioned to take advantage of the same kinds of rising air currents on certain planets/planet satellites to stay aloft for great periods of time to conduct meteorological and geological surveys. Gliders using this type of natural flight mechanism have greater mobility than balloons, are much lower in mass (and higher in payload fraction than balloons or powered air vehicles), and in suitable atmospheric condition can stay aloft longer than powered craft. Deployed in large numbers these flight systems can substantially enhance science return. These biomorphic systems would complement the capabilities of the larger exploration vehicles. Unlike other exploration platforms, the flight systems can cover distances of several kilometers in a very short time, nearly independent of terrain. Compared to surface crawler biomorphic explorers, biomorphic flight systems have the potential for substantially higher mobility (in speed, range, and terrain independence). Biomorphic flight systems can even be made to deliver other biomorphic explorers to target sites, greatly extending the utility of those explorers. These flight systems with their ability to land relatively softly, have the advantage of being a good means for distribution of payload.

A disadvantage of the existing microflyer[55] is the limited payload capacity. However, as shown in figure 10, biomorphic flyer designs such as the gliders or seed wing pods can offer much higher payload fractions. The payload mass fraction of a glider is much higher than for a propeller driven air vehicle because the powered flyer must carry the additional mass of the propulsion system (propeller, motor, gearing, battery and heat sink). The trade off with a powered aircraft will always be fuel (battery) versus payload. For a glider, there is no engine and hence no fuel etc. and therefore most of the available lift carrying capacity can be used for payload. A seed wing is even simpler in construction than a glider and can carry even higher payload fractions.

Three general overlapping categories have been defined earlier within the Microexplorers report[46], ('a' = 1 to 20 cc, 'b' = 10 to 200 cc, 'c' = 100 to 2000 cc). Biomorphic flight systems may also be categorized within these segments and amongst those illustrated in figure 10, the seed wing pod flyer could be in the regime a or b, the gliders and powered flyers would typically be in regime b or c. In addition to the size/volume classification, these flight systems may be categorized further by vehicle class, flight regime, deployment, propulsion, and method of control. A few examples within these classifications are given below:

<u>Class</u>: glider, powered, boost glider, balloon, helicopter, blimp, or autorotating seed wing

<u>Flight regime</u>: subsonic, transonic, or supersonic

<u>Deployment</u>: launch from surface, entry probe, orbiter, or from larger atmospheric platform

<u>Propulsion</u>: propeller, flapping, rocket, or unpowered

<u>Control</u>: autonomous, telerobotic, biomorphic controls, or uncontrolled

8. COOPERATIVE SCENARIOS FOR EXPLORATION

Cooperative mission scenarios utilizing a combination of biomorphic explorers with versatile mobility modes are conceptualized in this section. Cooperative exploration with a lander, a rover, and a multitude of inexpensive biomorphic explorers would allow comprehensive exploration at a low cost and with broad spatial coverage. For orbiters, landers, rovers, and manned missions, flight systems in particular provide a means for exploring beyond the visual range of on-board cameras. They aid in identifying targets of scientific interest and to determine optimal pathways to those targets. In the case of an orbiter or entry probe, a large number of gliders or seed wing pod flyers, for example, spread over a general region of interest could return in situ measurements to augment science from images taken from space.

Payloads can range from small cameras to specialized science experiments designed to measure geophysical, chemical, or atmospheric properties. The biomorphic flight system itself can be designed to seek out features of interest, crash at the target site, and then act as a homing beacon for a lander or rovers that would later conduct further experiments. For data return, multiple communication options such as daisy chain, beacon, global broadcast and/or heirarchical organization would be practical.

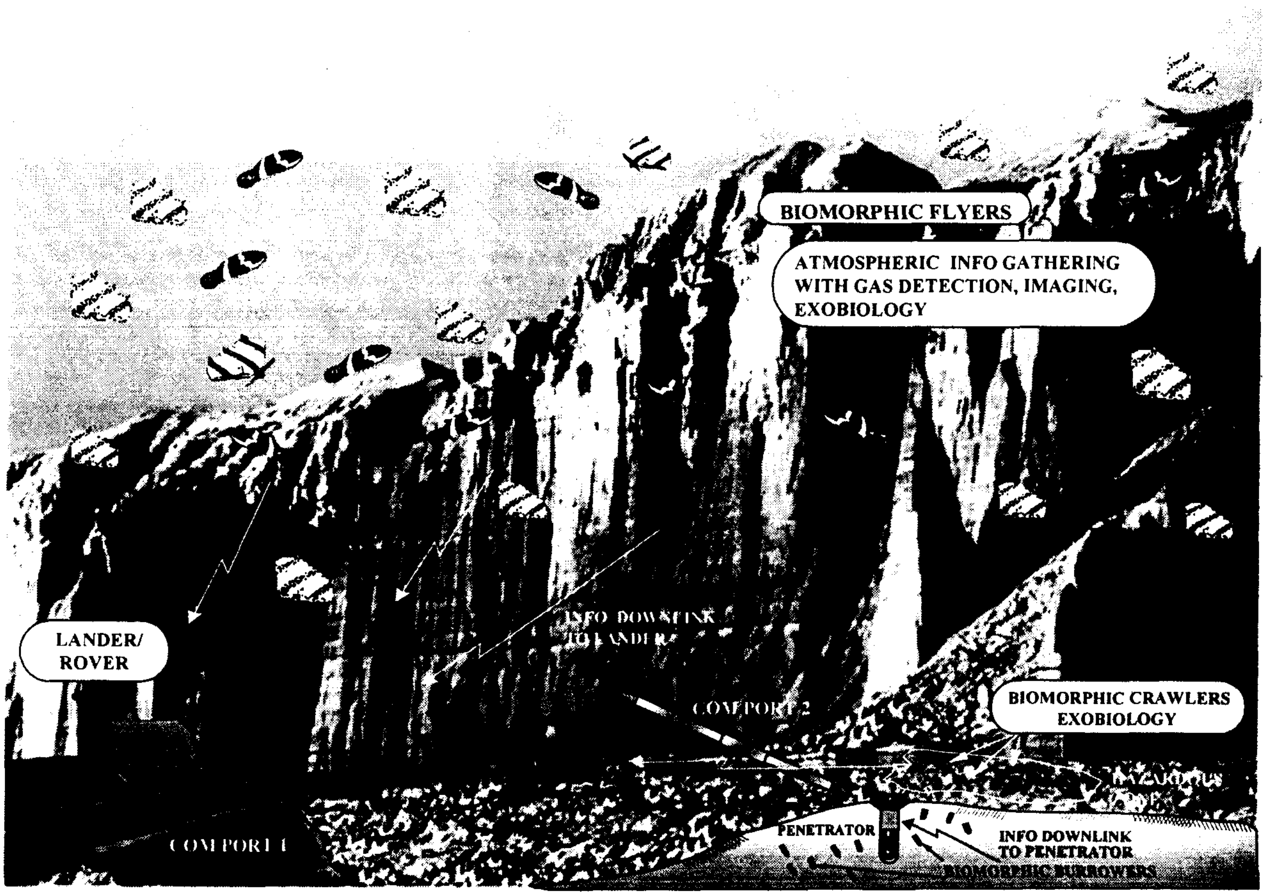

Figure 10: Concept for a Cooperative Scenario Utilizing a Heterogeneous Combination of a Lander/Rover and a Variety of Biomorphic Explorers

Figure 10 shows a co-ordinated co-operative mission scenario that capitalizes on the important capability of rapid mobility and extended reach.

The following mission concepts represent a small sample of the many potential mission scenarios available with biomorphic flight systems. Each scenario is written in a stand alone fashion and some of the same pertinent issues are addressed for each case independently.

8.1 Orbiter Based Seed Wing Pod Flyers for In Situ Measurement

Motivation:

The mission objective is to augment orbiter image data with in situ surface measurements. The information will also assist in identifying suitable lander sites for future missions. Orbiters have been used very successfully to obtain large scale geological and meteorological data. Although the information is extremely useful, image resolution is limited to several meters in scale due to practical constraints. Furthermore, in situ compositional measurements at specific sites of interest can significantly add to the science return and aid in future mission planning.

Mission Description:

After orbiting a planet or satellite (e.g., Mars, Titan) and sending images to Earth for several weeks, the science team identifies several regions of geological interest. One of three entry vehicles is launched from the orbiter so that the payload is released over a target area. The entry vehicle contains 100 or so small seed wing flyers, each equipped with a small surface probe, chemical experiment, camera or another specialized biomorphic/microexplorer. Seed wing pods are a very compact way of dispersing experiments / microexplorers over a broad area.

At an altitude of about 15 km, the entry vehicle begins a controlled release of the seed wing flyers, which autorotate to the surface. The entry vehicle will traverse 50 to 100 km during the course of releasing the seed wings. A straight, circular, or intelligent flight plan may be used. Meteorological information on weather patterns will be utilized to select the timing of release of the seed wings in this mission to maximize the science return.

After the seed wings have landed, each conducts a surface experiment that may consist of a surface probe and/or a chemical test, which analyzes for the presence of key trace elements. Next, the orbiter emits a signal initiating communications. The identified seed wing then transmits the results of its experiment. No return indicates a failure of that specific seed wing, or the signal is obscured by terrain so another attempt to communicate should be made from a different aspect angle. The orbiter receives the transmissions and locates each seed wing using a phased array antenna.

Two other regions of interest may be explored in the same manner with the remaining two entry vehicles and seed wing pods.

Impact on Orbiter Mission:

Mass - The total mass of the three entry vehicles and 300 seed wing pod flyers is on the order of 9 kg (10 g per seed wing, plus 2 kg per entry vehicle @ 50% payload mass fraction). In addition, the orbiter will have a phased array antenna ~1 kg mass.

Development cost and schedule - The seed wing is a passive entry device much like a parachute (only simpler). MEMS technologies are now being developed for chemical sensing that may be adapted for this application. The small scale, simplicity, and economies of scale with volume production suggest that this concept would be very low in cost and could be ready for deployment in a minimum of time. The entry vehicle development cost and schedule will most likely be dependent on the complexity of its flight profile. The simplest and cheapest will be a passively stable entry vehicle capable of gliding without controls or active stabilization and will most likely fly in a large circular flight path.

Risk - It is unlikely that incorporating this concept will in any way jeopardize the primary orbiter mission. Glider failure could be partly mitigated by triggering dispersal of all the seed wings before the entry vehicle impacts the surface. Some seed wings are expected to fail with little impact on the overall results. Improper placement of the seed wings will result in acquiring data for a site other than the preferred site.

Benefit - The benefits include in situ measurement of the mineralogical or chemical composition of soil at or near the surface to correlate with orbiter images. Key findings or validation of image data for use in selection of future lander sites would be valuable.

8.2 Orbiter Based Biomorphic Gliders for In Situ Measurement

Motivation:

The mission objective is to augment orbiter image data with in situ surface measurements and assist in identifying suitable lander sites for future missions. Orbiters have been used very successfully to obtain large scale geological and meteorological data. Although the information is extremely useful, image resolution is limited to several meters in scale due to practical constraints. Furthermore, in situ compositional measurements and higher resolution close-ups of specific sites of interest can significantly add to the science return and aid in future mission planning.

Mission Description:

After orbiting a planet or satellite (e.g., Mars or Titan) and sending images to Earth for several weeks, the science team identifies several regions of geological interest. One of three entry vehicle is launched from the orbiter so that the payload is released over the target area. The entry vehicle contains 25 or so small biomorphic gliders; each equipped with a small IR camera, surface probe, and a chemical experiment. At an altitude of about 12 km, the entry vehicle releases the gliders.

The gliders transition to flight and initially head out in a more or less random directions. Each glider is equipped to identify several geological features of interest based on a hierarchical list and using the IR sensor image. A high priority target feature is selected within its field of view and glide performance. The flight path is adjusted to intercept the target feature. (This is the search, identify, and target mode.)

En route, each glider in turn emits a weak signal identifying the type of feature targeted and the number of other feature classes identified within its glide range. Each glider also receives the signals from the gliders near it. Based on this information, gliders with a large number of neighbors targeting the same feature type have the option of selecting a different feature or adjusting course to seek new features thus insuring maximum dispersal and variation of science return.

After the gliders have landed, the orbiter emits a signal initiating communications with each of the gliders. The identified glider then transmits the last camera images for a close-up view of the surface. No return indicates a failure of that specific glider or that the signal is obscured by terrain. Another attempt to communicate should be made from a different aspect angle. While on the surface, the glider also conducts a surface experiment that may consist of a surface probe and a chemical test, which is analyzed for presence of key trace elements. This data is then included in the transmission. The orbiter receives the glider transmissions and locates each using a phased array antenna.

Two other regions of interest may be explored in the same manner with the remaining entry vehicles.

Impact on Orbiter Mission:

Mass - The total mass of the 75 gliders and three entry vehicles is 8.3 kg (assuming 50 g per glider plus 1.5 kg per entry vehicle). In addition, the orbiter will have a phased array antenna with ~1 kg mass.

Development cost and schedule - The glider is relatively simple due to the lack of a propulsion system. Also, flight performance and range is directly related to lift/drag and release altitude. As compared to powered flyers, the glider is relatively insensitive to mass and other design complexities which make the glider a fairly low risk development effort. Most technologies for flight related systems exist or are being proven through micro air vehicle (MAV) development. MEMS technologies are now being developed for chemical sensing and navigational aids which may be adapted for this application. The very small IR camera and biomorphic/multi-agent controls are likely the most difficult developments.

Risk - It is unlikely that incorporating this concept will in any way jeopardize the primary orbiter mission.

Benefit - In situ measurement of the mineralogical or chemical composition of soil at or near the surface can be used to correlate with orbiter images. Key findings and near surface image data will be extremely valuable in selection of future lander sites.

8.3 Lander-Based Electric-Powered Biomorphic Flyer Sample Return Mission Reconnaissance

Motivation:

The mission objective is to obtain samples from potential exobiology sites and areas of geological interest on Mars. Valles Marineris on Mars is a potentially favored landing site because, by comparison with our Grand Canyon here on Earth, it is expected to be potentially rich in geological units in one single site. Additionally, if accessible, it will be possible to sample the whole section from top to bottom from one single landing site. Bridger[49] has proposed a study of the entire stratigraphic column exposed along the canyon wall. Lucchita[50] has described Valles Marineris as an optimum science sample site. A lander equipped with a large rover (and ascent vehicle) lands in the Valles Marineris roughly 10 km from an area of potential exobiological significance, fault zones with exposed geological features, and eroded canyon walls with exposed sedimentary layers. The lander is targeted in a relatively flat area (devoid of interesting samples) to minimize risk in landing. The rover is designed for traversing rugged terrain and is equipped with an arsenal of scientific experiments including the ability to obtain and store samples. Unfortunately, the rover is expected to have a limited life, and there is always a risk of damage or loss in negotiating the rugged terrain. Therefore, some knowledge of the terrain and locations of scientific targets can significantly reduce mission risk and improve sample collection efficiency.

Mission Description:

After shedding the protective gear and making necessary deployments, a javelin is launched from the lander, and lands some 50 meters away. The javelin and lander begin emitting low-power RF signals, which will be used for radio navigation by the biomorphic flyers and other explorers. The canyons in the foothills of the Valles Marineris are varied[51], some with steep walls and rubble at the base; others are filled with wind-blown sands. Many canyons end abruptly after a short distance or become impassable due to rockslides. From its vantage point in the valley, the lander cannot determine the location of ideal science targets or the best paths to reach them. The rover could waste a tremendous amount of time searching for a suitable path and going down dead ends.

On board the lander are a dozen or so biomorphic flyers, each weighing about 100 g. One is launched from its garage using a metal spring to accelerate the flyer to flight speed. The flyer follows the heading specified by mission planners and transmits images from a small camera to the lander at regular intervals. Flight speed is roughly 70 meters per second, and after just over two minutes, the flyer is in the foothills. For the next minute or two, the flyer continues flying on the radial heading.

This particular biomorphic flyer also is equipped with the logic to identify specific features that may signify an area of scientific interest. The biomorphic flyer then makes a decision to terminate the flight when its sensor identifies a potential exobiological site. Its small size, low mass and rugged design enable it to survive the impact with the ground. It then deploys a small science experiment with a chemical or pyrotechnic device and a "sniffer" to determine the presence of some trace element. Perhaps this experiment might even burrow several centimeters below the surface. The biomorphic flyer then uses its remaining power and the power from a small photovoltaic cell to periodically transmit the results of its tests. This transmission also acts as a beacon.

The lander receives the images and beacon signal transmitted by the biomorphic flyers and relays them to the science team and mission planners on Earth via an orbiter. Several other biomorphic flyers are launched in succession, each on its own radial, and the images and data are collected and sent to the project team. Based on this data, the project team identifies target sites with the greatest science potential, and suitable pathways are mapped.

The rover then begins its mission with numerous radio beacons aiding in its navigation. Along the way, the rover finds itself unable to negotiate a way around some fallen rock and debris. The rover itself carries several biomorphic flyers, designed for slow flight, and deploys one to survey the area. Also, the rover could carry several biomorphic flyers to allow functional subdivision. Using the rover as a beacon, it takes images of the rover and surrounding area while sending the images back to the lander. Mission planners are able to use the information to plan an effective route – not to mention getting an image of the rover in a rugged remote location for the media. Little time is wasted and the risk is minimized. The rover executes its mission plan and obtains samples from several sites before returning to the lander and depositing the samples into the ascent vehicle. Biomorphic flyers could also be used to send the samples back to the lander for collection. In this reconnaissance role the biomorphic flyers maximize the effectiveness of the larger rover.

Impact on Lander Mission:

Mass - The total mass of the 12 flyers is about 1.2 kg (assuming 100 g per flyer). An additional 1 kg would be needed for the launcher and communications.

Development cost and schedule - This flyer concept is a derivative of the AeroVironment MAV's which have already been demonstrated in flight. Powered flight near the surface on Mars offers significant technical challenges, that will require more refined flight systems to further reduce mass. Significantly more complex than the gliders and with more stringent navigation requirements, the powered flyer would be a more costly development. Most technologies for flight related systems exist or are being proven through MAV development. MEMS technologies are now being developed for chemical sensing and navigational aids that may be adapted for this application. The very small IR camera and communications equipment providing high data rates with minimal power are most likely the most difficult developments.

Risk - It is unlikely that incorporating this concept will in any way jeopardize the primary lander mission. In fact, the flyers in this case are used to minimize mission risk.

Benefit - In situ measurements can be made of the mineralogical or chemical composition of soil at or near the surface over a broader area than the rover will be able to cover. Key findings and near surface image data will be extremely valuable in rover pathway selection and planning for maximum return (i.e. risk reduction).

8.4 Biomorphic Gliders for Sample Return Mission Reconnaissance

Motivation:

The mission objective is to obtain samples from potential exobiology sites and areas of geological interest.

Mission Description:

A lander equipped with a large rover and an ascent vehicle lands in the Valles Marineris roughly 10 km from an area of potential exobiological significance, fault zones with exposed geological features, and eroded canyon walls with exposed sedimentary layers. The lander is targeted in a relatively flat area (devoid of interesting samples) to minimize risk in landing. The rover is designed for traversing rugged terrain and is equipped with an arsenal of scientific experiments including the ability to collect samples for return. Unfortunately, the rover is expected to have a limited life and there is always a risk of damage or loss. Therefore, some knowledge of the terrain and locations of scientific targets can significantly reduce mission risk.

Gliders, equipped with a miniature camera and, possibly, a small IR detector and a simple surface experiment may be deployed to obtain intelligence for targeting specific sites of scientific interest and for planning rover pathways. The lander would most likely have to be in place within the Valles Marineris before glider deployment to minimize the transmit power required.

Perhaps as many as 50 small gliders are stored inside a simple passively stable entry vehicle. The entry vehicle would begin releasing the gliders near the top of the canyon walls at an altitude of about 14 km so they can glide down toward the bottom of the canyon at nearly a constant altitude above the surface. Each glider will use a small camera to take images of the terrain below and transmit the images to the lander, which will relay them to Earth via the orbiter. After landing, each glider may conduct a simple experiment or deploy another biomorphic explorer. It transmits the results to the lander while acting as a radio beacon. Each glider would be programmed for a specific flight trajectory based on navigation using the sun. Thus, the images may be geologically referenced using the beacon signal location. The project team uses the information to identify target sites with the greatest science potential and to map suitable pathways for the rover. The rover is then deployed having a mission plan and numerous radio beacons to aid in navigation.

Impact on Lander Mission:

Mass - The total mass of the 50 gliders and entry vehicle is about 9 kg (assuming 75 g per glider plus 5 kg for the entry vehicle).

Development cost and schedule - The glider is relatively simple because a propulsion system is not required. Flight performance and range is directly related to lift/drag and release altitude. The glider would be a low cost and fairly low risk development effort. Most technologies for flight related systems exist or are being proven through MAV development. MEMS technologies are now being developed for chemical sensing and navigational aids which may be adapted for this application. The very small IR camera and communications equipment with multiple data streams, high data and high power efficiency are likely the most difficult developments.

Risk - It is unlikely that incorporating this concept will in any way jeopardize the primary lander mission. In fact, the fliers in this case are used to minimize mission risk.

Benefit - The benefits include in situ measurements of the mineralogical or chemical composition of soil at or near the surface over a broader area than the rover will be able to cover. Key findings and near surface image data will be extremely valuable in rover pathway selection and planning for maximum return.

8.5 Biomorphic Gliders for Payload Deployment to the Polar Ice Cap

Motivation:

The mission objective here is to obtain historical climatology data on Mars through in situ compositional measurements, analogous to core samples, of the ice cap taken at various depths below the surface. The experiments are to be conducted at ten sites over a broad area (without specific targeting) to gain information on ice uniformity. The project is to be carried out as a piggyback micro-mission and the hardware is to be contained within one entry vehicle.

Mission Description:

During approach to Mars, the entry vehicle is released toward the polar ice cap. Gliders may be used to obtain images of the ice layers at the edges of the ice sheet. Contained inside the entry vehicle are 10 biomorphic gliders carrying one experiment each. At 15 km above the surface, the entry vehicle releases/disperses these gliders. The gliders are simple, passively stable, free flight (uncontrolled), platforms that glide in random directions traveling roughly 6 km forward for every 1 km lost in altitude. The total dispersal pattern for the 10 gliders will be roughly 100 km in diameter. Once on the surface, the glider shape is designed to minimize the chance of becoming airborne once on the surface, perhaps aided by use of an anchor.

Each glider carries a biomorphic explorer designed to burrow through ice, snow, and soil using a combination of scraping and heat while pulling debris around itself and applying downward pressure with its limbs. Upon landing, the burrowers begin digging into the surface. Power and communications with the spacecraft can be provided the burrower if needed by the glider via an umbilical cord, which is unwound as the burrower makes its progress. The glider is equipped with batteries, photovoltaic cells, and transmitter.

The limited light available for solar power implies that progress will be slow, but a simple spring-loaded panel with solar cells is released into a vertical orientation to maximize sun exposure and capture reflected light from the surrounding ice. Burrowing will periodically need to be stopped to enable the solar cells to recharge the battery. Once deployment is complete, there are no moving parts on the surface that must endure the harsh polar environment. The batteries would utilize self-heating and good insulation to maintain reasonable performance.

The burrowers would carry narrow-band LEDs or other instrumentation to detect different ice layers and possibly to determine composition (H_2O or CO_2). Measurements and reports on progress (depth) would regularly be transmitted to the orbiter.

Impact on Orbiter Mission:

Mass - The total mass of the 10 gliders, 10 burrowers, and the entry vehicle is about 3.5 kg (assuming 100 g per glider, 100 g per burrower, 1.5 kg for the entry vehicle).

Development cost and schedule - The glider is relatively simple due to the lack of a propulsion system. Flight performance and range are directly related to lift/drag and release altitude. The glider would be a low cost and fairly low risk development effort. Most technologies for flight and burrower support related systems exist or are being proven through MAV development. The burrower is likely to be the most expensive and risky development effort.

Risk - Use of multiple instruments and delivery vehicles helps to reduce mission risk significantly.

Benefit - In situ measurements of the ice cap can be made over a broader area than a single lander will be able to cover.

9. POTENTIAL APPLICATIONS:

The earlier sections of this report detailed cooperative scenarios relevant to planetary exploration. More generally, utilizing cooperative behaviors may be indicated in aspects of missions that are inherently distributed in space, time, or functionality. The advantages of distributed, cooperative exploration can include increased reliability and robustness (through redundancy), decreased task completion time (through parallelism), and decreased cost (through simpler individual explorer design). Also, a multitude of other applications exist in both the human exploration and development of space and in the terrestrial domain. A partial list of tasks that can be supported includes cleanup of hazardous waste, nuclear power plant decommissioning, search and rescue missions, construction, mining, automated manufacturing, industrial/household maintenance, security, surveillance, and reconnaissance.

10. CONCLUSIONS:

1. Cooperative behaviors observed in nature can suggest cooperative behaviors that could be beneficially utilized in planetary exploration missions. Keeping in mind the potential payoff to low cost, wide-spread exploration and a persistent presence in space, a broader and concerted study of cooperative behaviors in insect societies would be valuable.

2. Technologies needed to enable such cooperative behaviors should be a priority. These include the biomorphic flight system technology and cooperative multi-explorer biomorphic controls technology.

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